Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

SSC Magnet Technology

C. Taylor

September 1987

SSC MAGNET TECHNOLOGY*
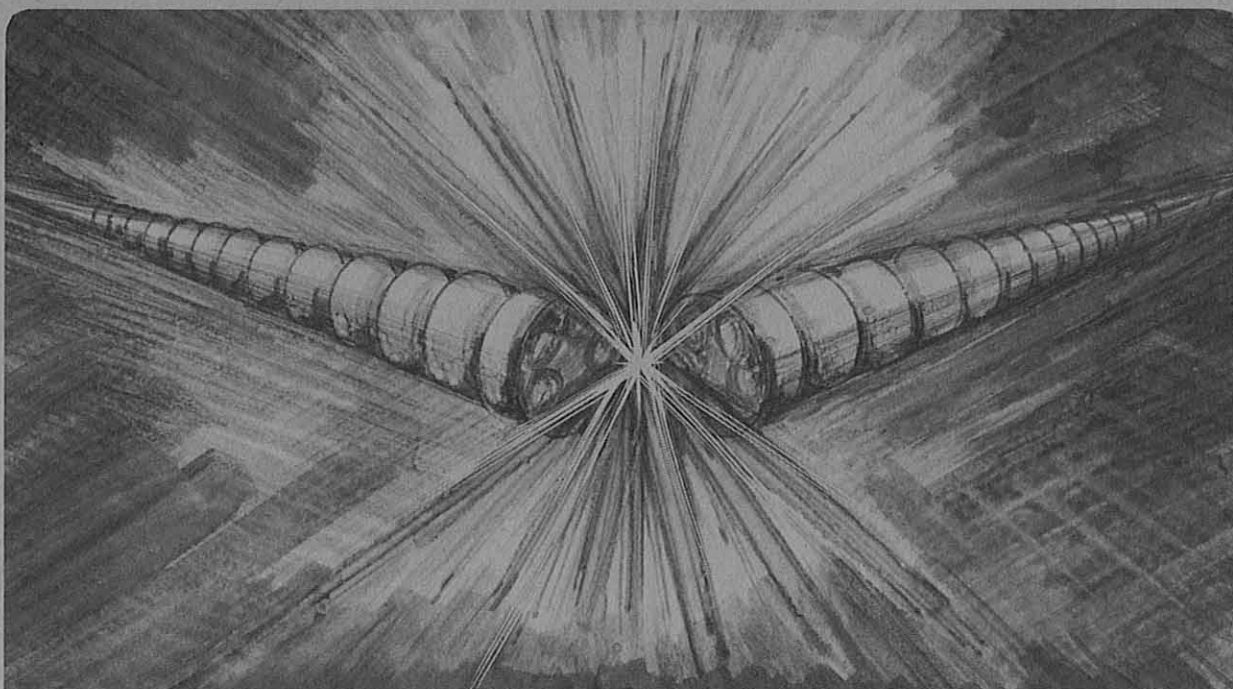
C. Taylor

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

September, 1987

SSC MAGNET TECHNOLOGY

C. Taylor

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720, USA

Abstract

To minimize cost of the SSC facility, small-bore high field dipole magnets have been developed; some of the new technology that has been developed at several U.S. national laboratories and in industry is summarized. Superconducting wire with high J_c and filaments as small as 5μm diameter is now produced with mechanical properties suitable for reliable cable production. A variety of collar designs of both aluminum and stainless steel have been used in model magnets. A low-heat leak post-type cryostat support system is used and a system for accurate alignment of coil-collar-yoke in the cryostat has been developed. Model magnets of 1-m, 1.8 m, 4.5 m, and 17 m lengths have been built during the past two years.

Introduction

The SSC (Superconducting Super Collider) is a proposed 20 TeV per beam p-p collider.[1] Because of the very large size and cost of this device, an extensive effort has been made to develop dipole magnets with high field (6.6T) to minimize the proton bending radius, small bore (40 mm), to minimize the cost per unit length, a very efficient cryostat, and long length (17 m) to minimize the number of units. This has required improvements in superconductor technology, magnetic design, collar design, and cryostat design. The project is in an R&D phase and the magnet design is still being improved, with emphasis on cost and reliability. Tests on short models of 1-m, 1.8 m, and 4.5 m lengths have been made and several full-length models have been built. Some of the major design features are described. The majority of the development work has been done by a collaboration of government laboratories: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), and Lawrence Berkeley Laboratory (LBL), together with U.S. industrial companies. The major parameters of the SSC magnets are given in Table I.

Table I. General Features of the SSC Magnet System

Proton energy per beam	20 TeV
Luminosity	10^{33} cm^{2}S
Beam energy/ring	396 MJ
Refill time	1 day
Injector energy	1 TeV
Acceleration time	15 min.
Magnetic field	6.6 T
Magnetic radius of curvature	10 km
Total circumference	86.6 km
No dipoles	7664
Dipole length - (Magnet/cryostat)	16.54 m/17.34 m
No. vertical beam dipoles	160
Arc quadrupole gradient	230 T/m
Quadrupole length (magnet/cryostat)	3.64 m/4.64 m
No. arc quadrupoles	1144
No. special quadrupoles	614

There are 7664 dipole magnets and 1144 quadrupole magnets in the main lattice cells, 160 dipoles for vertical bending, and about 614 special quadrupoles for focussing the beams at the six collision regions. Table II gives the major parameters of the dipole magnets.

Table II. Dipole Magnet Parameters

Operating field	6.6 T at 4.35K
Operating current	6500A
Inductance	53 mh
Stored energy	1.12 MJ
Coil configuration-2 layers	2-layer "cos θ" winding
Inner Layer-2 coils	
Inner diameter	40 mm
Outer diameter	59.2 mm
No. turns/coil	16
Cable width	9.296 mm (0.366 in)
Cable thickness (keystoned)	1.588 mm/1.326mm (0.0625 in/0.0522 in)
Strand diameter	0.808 mm (0.0318 in)
No. strands	23
Filament diameter (approx.)	6 μm
Cu/SC ratio	1.3/1
Wedge spacers/coil	3
Outer Layer-2 coils	
Inner diameter	59.7 mm
Outer diameter	79.9 mm
No. turns/coil	20
Cable width	9.728 mm (0.383 in)
Cable thickness (keystoned)	1.268 mm/1.062 mm (0.0499 in/0.0418 in)
Strand diameter	0.648 mm (0.0255 in)
No. strands	30
Filament diameter (approx.)	6 μm
Cu/SC ratio	1.8/1
Wedge spacers/coil	1
Collars - interlocking-keyed	
Radial width	15 mm
Thickness	1.52 mm
Laminated iron yoke, split at midplane	
Inner diameter	111.4 mm
Outer diameter	266.7 mm (10.5 in)
Weight of iron	5170 kg
Yoke containment shell	
Outer diameter	276.22 (10.875 in)
Thickness	4.76 mm (0.1875 in)
Cryostat - steel vacuum vessel, superinsulation	
O.D.	610 mm (24.0 in)
Wall thickness	6.35 mm (0.25 in)
Heat shield temp.	20K; 80K
Cold mass support	5 re-entrant posts

This report describes only dipole models; however, a 1-m quadrupole model was built and tested at LBL, reaching the design gradient of 230 T/m at 6500 A, using the dipole outer coil cable and interlocking aluminum collars.[2]

Cable

Because of the economic advantages of high current density, i.e., less superconductor, smaller diameter iron, etc., an effort has been made to develop reliable sources for high J_c, fine filament composite wire that can be fabricated into long continuous lengths of highly compacted cable. The SSC field uniformity must be very good throughout the acceleration cycle between 0.33T and 6.6T; however, at low fields, persistent currents within the superconducting filaments result in distortion of the dipole field.[3] This distortion is approximately proportional to filament diameter,[4] thus, small filaments are necessary to minimize the cost of complex auxiliary correction coils.

For example, with the present specification of 6 μm diameter filaments, the field distortion, $\Delta B/B$, at B_0 = 0.33 T, is ~ 10^{-3} at 1 cm radius and must be reduced by a factor of about 10 using a full length superconducting correction coil wound on the outside of the bore tube.[5] For the inner cable, a filament size of 6 μm requires about 7900 filaments per strand. Minimum distance between filaments must be about 0.8 μm to prevent tunneling currents passing through the copper matrix from causing excessive additional field distortions.[6] However, if the spacing is too large, the filaments can become distorted during wire fabrication because of the differences in mechanical properties between the hard superconductor and the relatively soft copper matrix. This distortion or "sausaging" can result in low critical current.[7] The maximum spacing for 6 μm filaments appears to be about 1.2 μm for optimum critical current depending on a variety of processing variables.

Filament-filament coupling can be nearly eliminated by mixing a small amount of manganese with the copper matrix.[8,9,10] This technique, if practical, would permit much smaller filaments to be used. However, the economics of producing wire with very large numbers of filaments has not yet been determined and magnets using this material have not yet been tested.

Figure 1 shows critical current density achieved in full-scale production of SSC strand over the past few years.[11] Improvements have been due to optimizing heat treatments, billet design, processing procedures, homogeneity of the NbTi, and quality control. The specified minimum current density is 2750 A/mm² at 5T, 4.2K. This is being achieved in production with very long continuous wire lengths. However, R&D samples of NbTi composites have been made with J_c of 3700 A/mm².[12] Degradation caused by cabling is generally less than 5%.

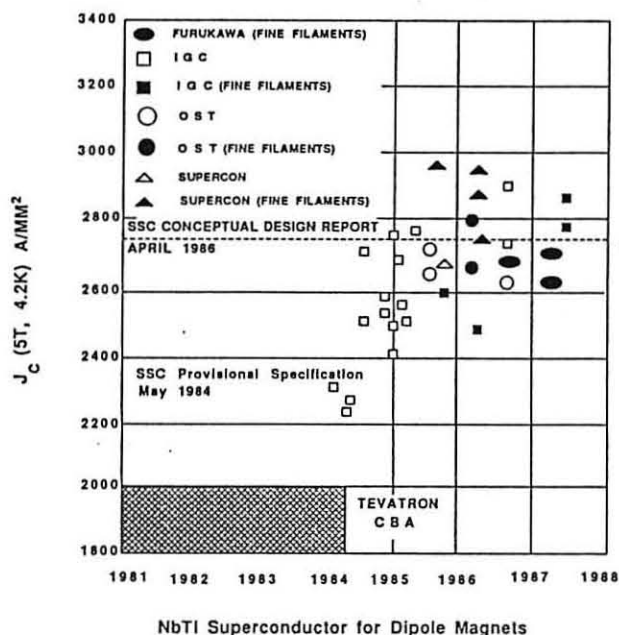NbTi Superconductor for Dipole Magnets

Fig. 1   NbTi Current Density vs. Date of Production for SSC Strand Made From Full Scale Billets.

Collars

Structural support of the coils is provided by interlocking collars; early designs used either stainless steel or aluminum alloy collars of nearly identical design, assembled into 6" long packs with alternate collars pinned together.[1] Two keys on each side lock the collar packs around the coils. The stainless steel collars are centered

within the iron yoke at four locations by close fitting tabs that are free to slide radially and axially; thus, magnetic forces are completely supported by the collars. This design has been used in numerous 1-m, 1.8 m, 4.5 m model magnets and four 17 m long models. In contrast, the aluminum alloy collars are centered at the two midplane tabs only, with clearance elsewhere. When the magnet is energized, deformation at the midplane is restricted by the iron yoke; thus, the magnetic forces are partially supported by the yoke. The resulting deformation of the windings under magnetic load is less than with stainless steel collars. The coils must be assembled with enough prestress so that the cable strands are very firmly supported and cannot move excessively as magnetic forces are applied. A major disadvantage of both designs has been the need to "oversqueeze" the coils during collar assembly to get enough clearance to insert the keys; after the keys are inserted and the load on the hydraulic press is removed, the collar diameter increases as the coil expands, thus decreasing the residual circumferential pressure. For example, to achieve the desired prestress of about 8000 psi (cold), the maximum pressure during key insertion is about twice this value and can cause damage to the electrical insulation between turns. This problem has been helped somewhat in the stainless steel case by spot welding alternating collars in pairs to increase rigidity.[13]

To eliminate this "springback", a new tapered key design allows the collars to be loaded without "oversqueeze" as the tapered keys are inserted hydraulically.[14] Figure 2 shows a cross section of the first magnet built with tapered keys. Several small design improvements have been made recently to facilitate assembly and to reduce the collar width at the midplane. This design works well and has been successfully tested with aluminum collars in 1-m model magnets. Similar designs are being developed for stainless steel collars.[15]
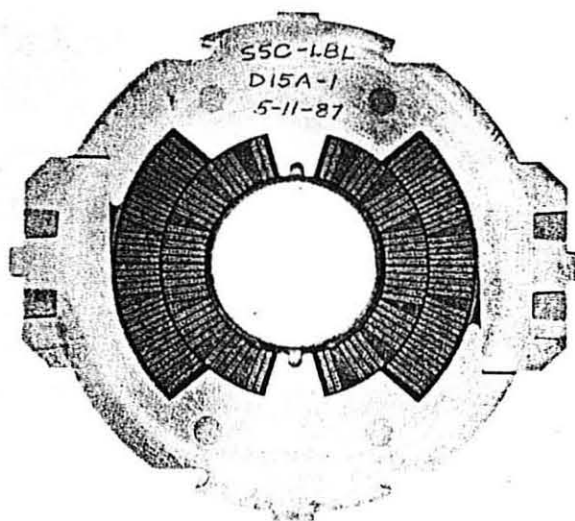

Fig. 2   Section of Collared Coil Showing Tapered Keys and Location of Cable in the Windings. CBB 881-52

Cryostat

The 276 mm O.D., ~16.5 m long cold mass is supported within the 610 mm diameter outer wall of the cryostat by five posts. Figure 3 shows a cross section of the existing design. To shorten the overall post length, a re-entrant or "folded" design is used, with a metal tension tube at 80K forming the link between the low heat leak compression tubes of fiber reinforced epoxy.[16] There is a heat shield at 20K, and another at 80K, with multilayer insulation (MLI) in the vacuum space surrounding the shields. Initial tests of a full-length cryostat verified that the design heat leak can be achieved.[17]
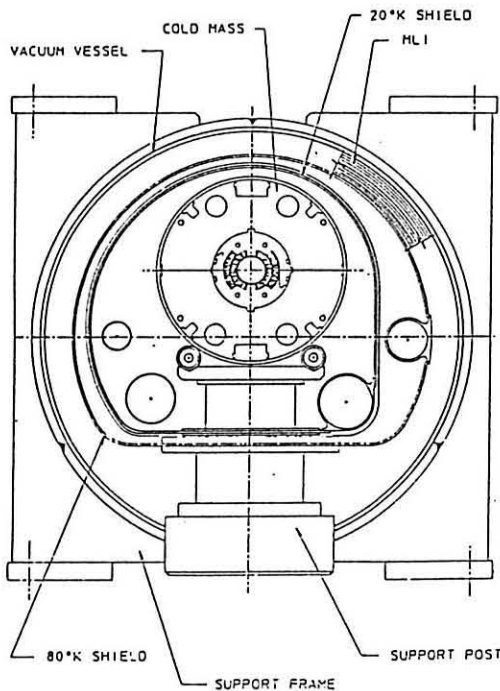
Fig. 3   Cross Section of Cryostat Design Used in the First
         17 m SSC Models.

The posts have relatively large diameter thin-walled tubes that can support lateral and axial loads as well as vertical loads and loads from transportation and seismic activity

To accommodate axial thermal contraction between the cryostat outer wall and the cold mass, the latter is fixed to the center post only and is permitted to slide axially at the four other posts using low friction bearing surfaces. Figure 4 shows a new design of the cold connection slide designed at FNAL[18] which uses the yoke shell of the cold mass as the bearing surface.
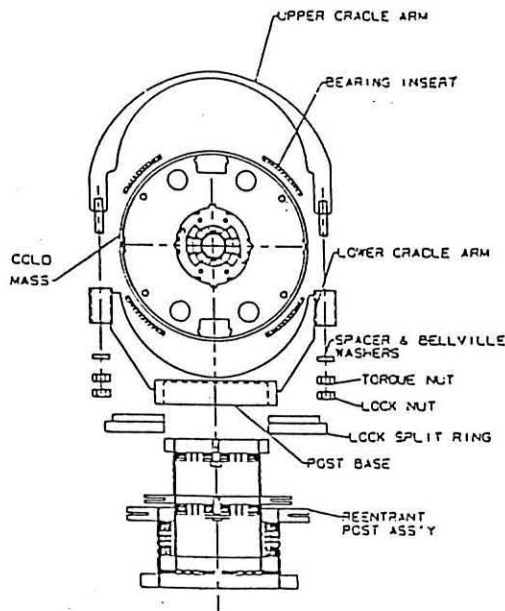

Fig. 4.   New Design of Thermal Connection Slide
          (Design B).

To more effectively withstand axial acceleration loads, a recent innovation[16] provides that each of the five posts be connected axially at the cold end to the adjacent post by a composite tube having a very low coefficient of thermal contraction, such as a graphite-epoxy composite. This allows the axial load to be shared among the five posts, rather than accepting the heat leak of either an additional axial support members, or a strong post at the center.

Graphite fiber rather than glass fiber is being evaluated for the 4.5K - 80K tube[16]; this would result in lower heat leak and greater stiffness. Extensive testing of various cryostat components is being conducted at FNAL before final design of the multilayer insulation, axial sliding bearing, and support post.

Magnet Model Results

Short models of SSC dipoles have been built and tested at BNL and LBL to verify electrical and magnetic performance; therefore, R&D cryostats were used. At BNL, stainless steel collars have been used in 1.8 m and 4.5 m models and at LBL, 1-m models have been built with both stainless steel and aluminum alloy collars. The short model tests have verified that adequate magnetic field quality and design field can be achieved with reasonable training behavior. Training behavior, field quality, and construction details for 1.8 m BNL models are described in reference (13).

Training behavior of 14 LBL models with aluminum collars is summarized in Fig. 5; models B-2 through B-6 were "conditioned" by operating the magnet initially at 7.2 T or higher without experiencing a quench by temporarily reducing the temperature to about 1.8 K.[19] Subsequently, the magnets operated at 4.4 K to full field without training. Conditioning was not done on the more recent magnets in order to reveal the influence of various design changes and parameters on training. In general, the models with more than two training quenches also appeared to have unusual features such as abnormally low prestress or shorted turns. Models A-1, A-2, A-3, and DSS-9 (a 1.8 m model that was tested at BNL) have tapered keys. All of the 1-m models were later tested at 1.8 K with most reaching fields greater than 9 T.
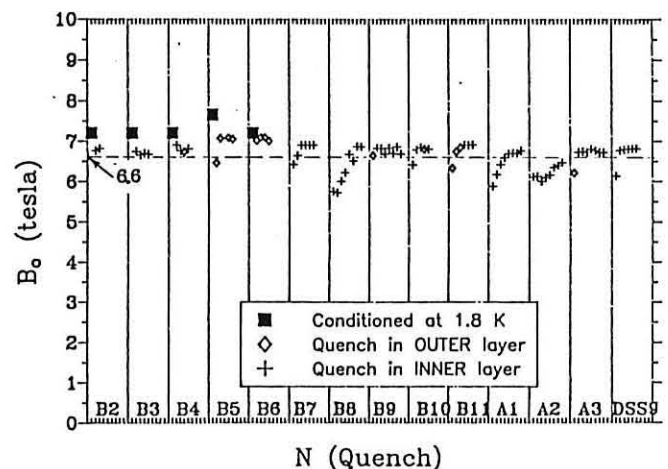

Fig. 5   Central Field vs. Quench Number for Recent LBL
         1-m Models.

17 m models of the cold mass assembly with stainless steel collars have been built at BNL,[20] assembled into SSC cryostats at FNAL, and tested using pressurized single phase helium at FNAL.[20,21]

To date, the four tests of 17 m models also show good field quality but have revealed excessive training behavior due to quenches localized in the ends[21]; 17 m models are now being built using improved methods of end support and aluminum collars with tapered keys. A test facility at FNAL is being modified to permit low temperature "conditioning" of long magnets, a treatment which eliminates training in short models.

Cable of adequate quality is now being manufactured, adequate magnetic field uniformity,[12,22] and stability has been demonstrated in short models, and cryostat performance has been verified in a full length model.[23] Early long models have had excessive training quenches; however, the problem appears to be localized at the ends and several long models with many improved design features are now being built and will be tested in early 1988.

Acknowledgement

The work described in this paper represents the efforts of a large number of people, especially the magnet development groups at BNL, FNAL, and LBL, as well as the SSC Central Design Group and manufacturers of superconducting wire and cable.

References

1. SSC Central Design Group, "Conceptual Design of the Superconducting Supercollider," Lawrence Berkeley Laboratory, CDG SSC-SR-2020, March 1986.

2. C. Taylor, S. Caspi, M. Helm, K. Mirk, C. Peters, and A. Wandesforde, "A High Gradient Quadrupole Magnet for the SSC," Lawrence Berkeley Laboratory, LBL-22266, Proceedings of the 1987 Particle Accelerator Conference, Baltimore, MD, March 1987.

3. S. Caspi, W.S. Gilbert, M. Helm, and L.J. Laslett, "The Effects of Filament Magnetization in Superconducting Magnets as Calculated by POISSON," Lawrence Berkeley Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 510, March 1987.

4. M. A. Green, "Control of the Fields due to Superconductor Magnetization in the SSC Magnets," Lawrence Berkeley Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 506, March 1987.

5. P. Wanderer, J. Herrera, P. Thompson, and E. Willen, "Performance of R and D Sextupole Trim Coils for SSC Dipoles," Brookhaven National Laboratory, Proceedings of the 1987 Particle Accelerator Conference, Baltimore, MD, March 1987.

6. A. K. Ghosh, W. B. Sampson, E. Gregory, and T. S. Kreilick, "Anomalous Low Field Magnetization in Fine Filament NbTi Conductors," Brookhaven National Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 1724, March 1987.

7. E. Gregory, T. S. Kreilick, and J. Wong, Supercon, Inc., A. K. Ghosh and W. B. Sampson, Brookhaven National Laboratory, "Importance of spacing in the development of high current densities in multifilamentary superconductors," published in Cryogenics 1987, Vol. 27, p. 178, April 1987.

8. E. W. Collings, "Stablizer Design Considerations in Fine-Filament Cu/NbTi Composites," Battelle Memorial Institute, Proceedings of the 1987 CEC/ICMC Conference, St. Charles, IL, June 1987.

9. E. Gregory, T. S. Kreilick, and J. Wong, Supercon, Inc., R. M. Scanlan, Lawrence Berkeley Laboratory, A. K. Ghosh and W. B. Sampson, Brookhaven National Laboratory, and E. W. Collings, Battelle Memorial Institute, "Reduction of Coupling in Fine Filamentary Cu-NbTi Composites by the Addition of Manganese to the Matrix," Proceedings of the 1987 CEC/ICMC Conference, St. Charles, IL, June 1987.

10. A. Ghosh, W. Sampson, E. Gregory, T. S. Kreilick, and J. Wong, "The effect of magnetic barriers on the magnetization and critical current of fine filament Cu-NbTi composites," Brookhaven National Laboratory, September 1987, elsewhere in these proceedings.

11. R. Scanlan, Lawrence Berkeley Laboratory, Berkeley, CA (private communication).

12. S. Hong, Oxford Superconducting Technology Co., Carteret, NJ (private communication).

13. P. Wanderer, J. Cottingham, P. Dahl, M. Garber, A. Ghosh, C. Goodzeit, A. Greene, J. Herrera, S. Kahn, E. Kelly, G. Morgan, A. Prodell, W. Sampson, W. Schneider, R. Shutt, P. Thompson, and E. Willen, "Test results from 1.8 M SSC model dipoles," Brookhaven National Laboratory, September 1987, elsewhere in these proceedings.

14. C. Peters, K. Mirk, A. Wandesforde, and C. Taylor, "Use of Tapered Key Collars in Dipole Models for the SSC," Lawrence Berkeley Laboratory, LBL-23110, September 1987, elsewhere in these proceedings.

15. C.. Goodzeit, Brookhaven National Laboratory, Upton, L.I., NY (private communication).

16. T. H. Nicol, R. C. Niemann, and J. D. Gonczy, "SSC Magnet Cryostat Suspension System Design and Performance," Fermi National Accelerator Laboratory, Proceedings of the 1987 CEC/ICMC Conference, St. Charles, IL, June 1987.

17. R. C. Niemann, J. A. Carson, N. H. Engler, J. D. Gonczy, T. H. Nicol, J. G. Otavka, R. J. Powers, and J. C. Theilacker, "Design, Construction and Test of a Full Scale SSC Dipole Magnet Cryostat Thermal Model," Fermi National Accelerator Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 490, March 1987.

18. E. T. Larson, J. A. Carson, T. H. Nicol, R. C. Niemann, and R. A. Zink, "Improved Design for a SSC Coil Assembly Suspension Connection," Fermi National Accelerator Laboratory, Proceedings of the 1987 CEC/ICMC Conference, St. Charles, IL, June 1987.

19. W.S. Gilbert and W.V. Hassenzahl, "1.8K Conditioning (Non-Quench Training) of a Model SSC Dipole," Lawrence Berkeley Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 1229, March 1987.

20. P. Dahl, J. Cottingham, M. Garber, A. Ghosh, C. Goodzeit, A. Greene, J. Herrera, S. Kahn, E. Kelly, G. Morgan, A. Prodell, W. Sampson, W. Schneider, R. Shutt, P. Thompson, P. Wanderer, and E. Willen, "Construction of Cold Mass Assembly for Full-Length Dipoles for the SSC Accelerator," Brookhaven National Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 1215, March 1987.

21. B.C. Brown, M. Kuchnir, R. Lundy, P. O. Mazur, P. Mantsch, J. Strait, J. Cottingham, P. Dahl, H. Garber, A. Ghosh, C. Goodzeit, A. Greene, J. Herrera, S. Kahn, E. Kelly, G. Morgan, A. Prodell, W. Sampson, W. Schneider, R. Shutt, P. Thompson, W. S. Gilbert, W. V. Hassenzahl, R. Meuser, C. Peters, J. Rechen, R. Royer, R. Scanlan, C. E. Taylor, J. Tompkins, "Tests of prototype SSC magnets," Brookhaven National Laboratory, September 1987, elsewhere in these proceedings.

22. S. Caspi, W. Gilbert, M. Helm, L.J. Laslett, and C. Taylor "Development of a 40 mm Bore Magnet Cross Section with High Field Uniformity for the 6.6T SSC Dipole," Lawrence Berkeley Laboratory, published in IEEE Transactions on Magnetics, Vol. Mag-23, No. 2, p. 1219, March 1987.

23. R. C. Niemann, W. N. Boroski, J. D. Gonczy, T. H. Nicol, J. G. Otavka, R. J. Powers, and M. K. Ruschman, "SSC Dipole Magnet Cryostat Thermal Model Measurement Results," Fermi National Accelerator Laboratory, Proceedings of the 1987 CEC/ICMC Conference, St. Charles, IL, June 1987.